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FLOW IN CYLINDRICAL SEDIMENT TRAPS

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ABSTRACT. Flow behavior in cylindrical settling traps was observed in steady flow for trap Reynolds numbers (Re) between 1,600-30,500. The effects due to aspect ratio, wall thickness, a funnel at the bottom of the trap, and the presence of a mooring line were investigated. Although the data are semiquantitative, they show that upwelling frequency and intensity increased as Re increased and as the aspect ratio decreased. The relationships between the thickness of the bottom layer, the frequency of upwelling, and the settling velocity of a particle determines whether deposition occurs through the bottom tranquil layer or the viscous sublayer. Since the thickness of the bottom tranquil layer can be scaled by the trap diameter, the settling behavior of particles cannot be modeled simply by Re and the aspect ratio, as can flow behavior, but also depends on the ratio of flow velocity to settling speed. Flow behavior induced by wave action is similar in many ways to that generated by steady flow at the same Re. Depending upon flow conditions in the trap, either the measured flux or the size distribution of the material collected may differ substantially from that outside the trap. Traps that are designed so that upwelling does not occur during their deployment will give the best estimates of flux and particle distribution. This means that in most cases several small traps are preferable to a single large trap.
ADDITIONAL INDEX WORDS: Sedimentation, flux, fluid dynamics.

INTRODUCTION

In recent years a number of people have examined the collection efficiency of various types of sediment traps and the factors affecting that efficiency. Lau (1979) determined the conditions necessary to flush neutrally buoyant spheres out of cylindrical traps and found that his results could be explained by the interaction of two parameters—the trap Reynolds number (Re = inner trap diameter times current velocity divided by kinematic fluid viscosity) and the aspect ratio (A = trap height divided by the inner trap diameter). His experiments, which spanned a range of Re from 2,000 to 30,000 and aspect ratios from 4.7 to 10, showed that the minimum aspect ratio required to prevent resuspension was a logarithmic function of Re. Hargrave and Burns (1979) applied dimensional analysis to trap design and concluded that cylinders were the best shape to use. Their laboratory and field tests showed that trap collection efficiency increased as A increased to about 5, but that at higher values the efficiency remained fairly constant. Bloesch and Burns (1980) extended the theoretical analysis and formulated two primary criteria for trap design: first, since particle collection occurs by fluid exchange, particle concentration should be the same inside and outside of the trap; and second, in order to avoid resuspending previously deposited particles there should be a region of tranquil water at the bottom of the trap. They concluded that cylindrical traps with adequate aspect ratios met these criteria, with the required aspect ratio depending upon Re. Their field results suggested that an aspect ratio of 10 was appropriate for Lake Erie. Blomqvist and Kofoed (1981) compared the collection efficiencies of traps with constant aspect ratio but different diameters (10-40 mm) and found that although the amount of inorganic material collected increased with increasing diameter, the amount of organic matter decreased. They also tested traps with equal diameters but different aspect ratios and found that collection efficiency was essentially constant for A > 3. Unfortunately, Re was not reported. Gardner (1980a, 1980b) conducted both field and laboratory investigations on collection efficiency and found that traps with aspect ratios between two and three more accurately measured particle fluxes for Re up to 37,500. He also used dye to study the flow of water inside the traps at low Reynolds numbers (less than 3,000). In a study of the effect of tilt on trap collection efficiency, Gardner (1985) extended his investigations of flow behavior up to Re = 11,800. Butman *et al.* (1986) conducted a thorough theoretical analysis of trap collection efficiency and, based on their findings and on previous experimental results, concluded that for cylindrical traps in which the other two factors remain constant: 1) collection efficiency may decrease over some range of increasing Re, 2) collection efficiency may increase over some range of increasing aspect ratio, and 3) that collection efficiency may decrease over some range of decreasing particle fall velocity. In a subsequent laboratory study, Butman (1986) tested the first two of these hypotheses and found that: 1) for A = 3, collection efficiency decreased by about 50% as Re increased from 2,200 to 4,400, but remained approximately constant at higher Re (up to 19,000), and 2) although collection efficiency decreased about 40% as the aspect ratio increased from 1 to 2.7, there was no further decrease when A = 3.6 (Re = 10,000).

Although much work has been done, it is difficult to put the various pieces together, even if we restrict ourselves to cylindrical traps. Most of the investigations cover a limited range of Reynolds numbers and use traps with different aspect ratios. In addition, the Reynolds numbers in most of the field experiments are only approximate and may have varied substantially during the collection period, while most of the laboratory investigations have been done at Reynolds numbers much lower than those encountered in many natural settings. To date Butman's (1986) results are the most complete and systematic, but even these cover only a limited number of aspect ratios and Reynolds numbers. Gardner's (1980a, 1985) flow studies help to fill in the gaps and provide insights into the causes of the changes in collection efficiency, but the coverage is not complete. This paper presents the results of a systematic investigation of changes in flow behavior as a function of Reynolds number for Re from 1,600 to 30,500. In addition, the effects of changes in the aspect ratio, changes in the wall ratio (W = inner trap diameter divided by wall thickness), and the presence of a mooring line were considered. The results are used to describe changes in flow behavior as a function of Re and A. The effects of these changes on trap collection efficiency are then described and compared to previous experimental results. The first observations of flow behavior in traps due to wave action are also presented.

PROCEDURE

The investigation was designed to examine the behavior of the traps used by the Great Lakes Environmental Research Laboratory (GLERL) in the Laurentian Great Lakes. These traps are cylindrical with an inside diameter of (in most cases) 101.6 mm. Currents in the lakes typically are between 10 and 300 mm/s so the trap Reynolds number (Re) varies between approximately 1,000 and 30,000 with a change in current velocity of 10 mm/s causing a change in Re of about 1,000 (This calculation assumes that the kinematic viscosity is 0.01 Stokes, the value for water at 20°C. This is the value used in all the calculations in this paper). The traps have a funnel mounted at the bottom which leads into a collection bottle so that deposited material is continuously removed from the trap (Fig. 1). The aspect ratio (with height measured from the top of the trap to the top of the funnel) of the traps is 5, and the wall ratio is 16. Until 1983 the traps were mounted with band clamps directly on the mooring line; since that time they have been mounted about six wire diameters away from the line. In both cases the mooring line is upstream of the trap—a configuration that should be avoided according to Bloesch and Burns (1980). In addition to our 100-mm traps we have also used 150-, 200-, and 300-mm diameter traps. These also have an aspect ratio of 5.

Model traps were constructed to observe flow behavior for Re between 1,600 and 30,500. Dimensions of the traps and the range of Re over which they were used are given in Table 1. All the traps except numbers 7 and 9 have flat bottoms and were constructed by gluing lengths of clear acrylic tubing to lucite bases. Trap 9 is a pipette tip and trap 7 is constructed like the field traps with a funnel at the bottom. The effect of a mooring line on trap circulation was simulated by attaching a nail to the upstream side of trap 2 with the ratio of the nail width to trap diameter equal to the ratio of the mooring line diameter to our 100-mm traps (1:16). Changes in flow behavior due to changes in Re were the same regardless of whether Re was altered by changing the trap diameter or by changing the flow velocity. This confirms the Reynolds number

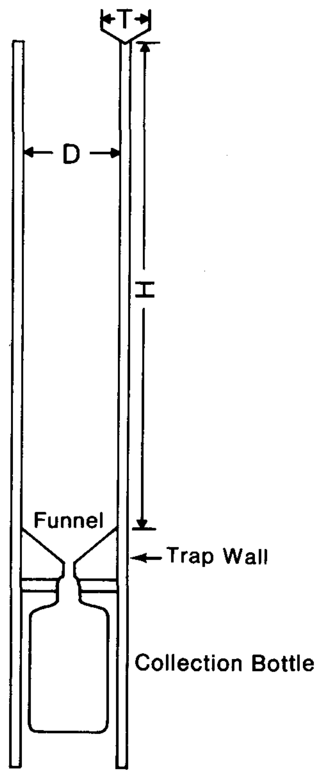

FIG. 1. Sample sediment trap showing the dimensions referred to in the text. Aspect ratio (A) = H/D, wall ratio (W) = D/T.

TABLE 1. Dimensions of the model traps. The Re range is for those traps used in the steady flow experiments. All of the traps except numbers 7 and 9 have flat bottoms.

Trap #	Diameter (cm)	Aspect Ratio	Wall Ratio	Re range
1	2.86	5	18	1,600–12,200
2	5.08	5	16	3,100–30,500
3	2.86	3	18	2,200–10,800
4	5.08	3	16	10,900–11,600
5	2.86	5	9	1,600–8,100
6	2.86	3	9	6,100
7	5.08	5	18	6,500–12,400
8	10.16	5	32	Not used
9	1.27	5.5	16	Not used
10	2.86	2	18	1,400–2,900
11	2.86	1	18	500
12	2.86	8	18	2,900–20,000

scaling and justifies the application of the results to larger traps.

Flow behavior was examined using potassium permanganate crystals which were placed on the trap bottom and on the trap walls by mounting them in a thin film of petroleum jelly. The dye released by the crystals allowed the motion in different parts of the trap to be observed for up to several hours. Since the dye is slightly heavier than water, downward motions were slightly enhanced and upward motions slightly inhibited. The crystals on the bottom of the trap generated a colored bottom layer whose thickness varied with the flow conditions. Upwelling at the bottom caused dye to be ejected from the bottom layer and its thickness to decrease. About half of the 83 runs were recorded on 8 mm film for subsequent analysis. Observations were made 10–15 minutes after the start of each run—the same time interval used by both Lau (1979) and Butman (1986). One experiment which ran for 3 hours (A = 5, Re = 4,900) showed that 10–15 minutes is not long enough to attain a near-equilibrium state. Observations of the thickness of the bottom layer showed a progressive thinning for the first hour (0.75 trap diameters after 10 minutes, 0.33 diameters after 25 minutes, and 0.2 diameters after 1 hour), but no change in the next 2 hours. Although longer runs would have given better estimates of the bottom layer thickness at equilibrium, lack of time and a desire to compare these results with those of other investigators dictated the shorter runs. Thus although the trends reported here are correct, the actual values reported for the bottom layer thickness are probably higher than those that would exist at equilibrium conditions, particularly at low Re.

Steady flow experiments were conducted in the GLERL test tank which has a test section 2.29 m long and 0.61 m wide. Water depth was 0.48 m during the runs. Traps were placed along the centerline of the tank 0.94 m from the entrance baffles. The tops of the traps were always at least 0.20 m below the surface and at least 0.20 m above the bottom. Water temperature was 20°C. The wave experiments were conducted in the University of Chicago wave tank which is 19 m long and 0.71 m wide. Still water depth was 0.60 m. The traps were placed in the middle of the tank about 5 m from the wave generator with the top of the trap 0.10 m below still water level. Water temperature was 20°C. In both facilities water temperature varied by less than 1°C.

Currents were measured using a Marsh-

McBirney 511 current meter with a 5 second time constant. Measurements were made at the same depth as the top of the trap prior to the beginning of the visual observations. The same meter was used for the wave measurements but the time constant was adjusted to 0.2 seconds. Measurements of both vertical and horizontal velocity were made every 0.4 seconds at a location about 1 m downstream (away from the wave generator) at the same depth as the top of the traps (0.1 m). Although the filmed observations and the current meter measurements were made concurrently, it was not possible to synchronize them. The generated waves had a period of 1.5 seconds and a height of 0.1 m but since absorption of the waves was incomplete, some reflection occurred which caused the waves to increase in size during the experiments. At no point did the trap break the surface. Wave Re were calculated as the root mean square of all the velocity measurements (between 70 and 130 per run). The velocity readings are probably somewhat high since Aubrey and Trowbridge (1985) have noted an 8% offset in the response of similar current meters in oscillatory flow. This error does not affect the sequence of flow changes observed, but it does mean that the Re reported are probably overestimates.

RESULTS

Over 80 runs were done in steady flows with Re between 1,300 and 30,500. Trap dimensions are given in Table 1. These runs investigated how flow behavior varied due to:

1. Increasing Re
2. Changing the aspect ratio (A)
3. Changing the wall ratio (W)
4. The effect of the mooring line
5. Replacing the flat bottom with a funnel.

Since the most fundamental changes occur as a result of increasing Re, they are discussed first. The other effects merely shift the value of Re at which these changes occur.

The basic elements of trap flow have been described by Gardner (1980a, 1985) who described three regions of flow. In the upper region of the trap flow within the trap is directly coupled to the external flow. Circulation is dominated by eddies which rotate counterclockwise (if the external flow is from right to left) as they are shed from the upstream trap wall. Some of these eddies go into the trap where they cause water to be ejected from the trap at the upstream wall and pulled into the trap on the downstream side. Below this upper region is a zone where the circulation is less consistent. Eddies may exist but they are not directly coupled to the external flow. Reverse eddies generated by the eddies in the upper zone sometimes occur in this zone. In the bottommost region of the trap, the water is tranquil at low Re but helical upwelling occurs at higher Re. The observations in this study agree with Gardner's, but allow a more systematic description of the changes that occur as Re increases. The general progression is the same for all aspect ratios – as Re increases, the depth of eddy penetration (E_D) increases, circulation in the middle zone becomes more vigorous, and the thickness of the bottom layer (B_T) decreases. The bottom layer also becomes disrupted more frequently by upwelling events until it ceases to exist. The observations show that if the depth of eddy penetration and the thickness of the bottom tranquil layer are measured in terms of the trap diameter (D), the results using traps with different diameters are consistent. Thus the relevant length scale is D when considering the flow behavior in traps. The synthesis presented below refers to traps with A = 5, and is based on 32 runs using traps 1 and 2 for Re between 1,600 and 30,500. The observations tabulated in Table 2 showed considerable variability. Since the values of E_D and B_T varied both between runs and during an individual run, the results are only semi-quantitative. Also, since the runs were probably not long enough to approach equilibrium conditions, both the values of B_T and the critical values of Re and A necessary for upwelling are probably too high. There was enough consistency between runs however, to make the following observations.

At low Re (1,600), the eddies in the upper region penetrate to about one trap diameter. Circulation just below this depth is weak and not well organized although some motion is evident. A completely tranquil region exists at the bottom of the trap at all times. As Re increases to 4,300 the depth of eddy penetration increases to 2–2.5 D (Fig. 2a), circulation in the middle zone increases as eddies are formed, and the thickness of the bottom layer decreases from about 4 D to 0.75 D.

At intermediate Re (4,900 < Re < 12,000) the upper layer is 2–2.5 D thick and reverse eddies become more common in the middle zone as the circulation intensifies. Flow in the lower zone is intermittent with upwelling events alternating with quiet periods. At Re up to 8,000 the upwelling usually occurs only at small spots at any one time, not

TABLE 2. Characteristics of trap flow as a function of Re and A. Eddy depth and bottom thickness are measured in trap diameters (D). Bottom thicknesses are those observed between resuspension episodes. Local resuspension means that resuspension was observed over only a small portion of the trap bottom at any given time. Re for wave action was calculated using the horizontal velocity. Very infrequent upwelling means that upwelling occurred less than about 20% of the time, infrequent means about 20-40%, intermittent 40-80%, and almost continuous 80-99%.

Re	Eddy Depth	Bottom Thickness	Upwelling
		A = 8	
2,900	1.5	5	None
4,300	1.5-2	3.25	None
6,300	2	3	None
7,800	2-2.5	2.33	None
9,800	2-2.5	2.33	None
12,500	2-2.5	2.10	None
15,300	2-2.5	1.90	None
18,400	2-2.5	1.50	None
20,000	2-2.5	0.75	None
		A = 5	
1,600	1	4	None
3,000	2	1.5-2	None
4,300	2-2.5	1.25-0.75	None
4,900	2-2.5	0.75	Very infrequent
6,000	2-2.5	0.5	Very infrequent
7,300	2-2.5	0.25	Infrequent, local
8,000	2-2.5	0.25	Infrequent, local
8,500	2-2.5	0	Almost continuous, local
10,000	2-2.5	0	Continuous, local
12,000	2-2.5	0	Continuous
		A = 3	
1,300	0.5	2	None
1,600	1-1.5	1.25	None
2,700	1-1.5	1-0.5	None
3,500	1.5	0.5-0.25	Infrequent
4,000	1.5-2	0.5	Intermittent
5,100	2-2.5	0.125	Almost continuous
6,000	2.5	0	Continuous, local
11,000	2.5	0	Continuous
		A = 2	
1,400	0.75	0	Infrequent
1,900	1-1.25	0	Almost continuous
2,900	1.5-2	0	Continuous
		A = 1	
500	1	0	Continuous
		Wave action, A = 5	
2,200	2	2	None
4,800	2.5	1	Infrequent
7,500	2.5-3	0.5	Intermittent
14,000	3	0	Continuous

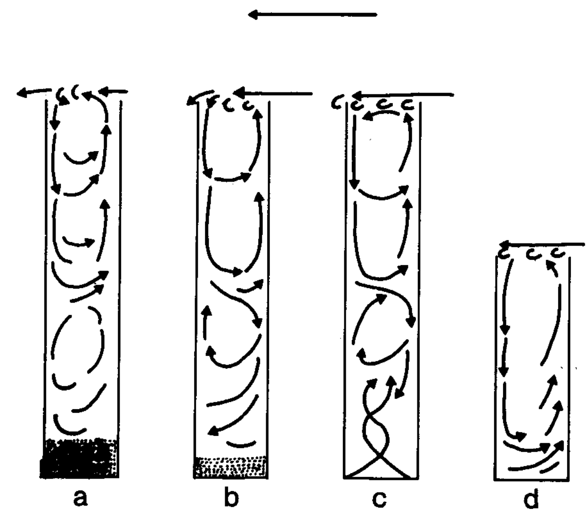

FIG. 2. Flow in traps generated by steady flow at various Re. For a-c, A = 5, for d, A = 3. Re = 4,300 for a, 8,000 for b, 10,000 for c, and 6,000 for d.

over the entire trap bottom. These locations are usually located on the upstream side of the trap. Although some of the water displaced during the upwelling escapes from the trap, most does not. As Re increases to 8,000 the thickness of the bottom layer decreases to 0.25 D and the upwellings become more frequent and last longer (Fig. 2b). At Re = 8,500, upwellings covering the entire trap bottom begin to occur. They are apparently the result of occasional reverse eddies that penetrate to the bottom. These upwellings generate a helical pattern as the water ascends into the middle zone (Fig. 2c. This pattern is almost impossible to draw—it looks like a double helix.). At Re> 12,000 there is almost continuous upwelling across the entire bottom; a tranquil bottom layer no longer exists at any time. The helical pattern becomes less pronounced as the eddies in the middle zone become stronger with increasing Re. Flow in the upper zone also increases in velocity but does not penetrate below about 2.5 D.

Decreasing the aspect ratio to 3 reduces the Re required for continuous upwelling to 5,100. At this value the upper eddies penetrate to 2-2.5 D and are close enough to the bottom to entrain all the water in the trap. The middle and lower zones cease to exist as upwelling occurs over the entire trap bottom (Fig. 2d). Even at Re = 3,500 there is some movement at the bottom of the trap. These observations are based on 11 runs using traps 3 and 4. Re varied between 1,300 and 11,600.

For A = 2 upwelling occurs even at the lowest Re tested (1,400). At this Re only a small percentage of the eddies shed by the upstream trap wall are entrained into the trap—most of them are lifted over the trap wall and are dissipated in the flow. Those that are entrained penetrate only about 0.75 D, but this is far enough to cause some upwelling at the bottom. A very thin bottom layer (about 3.0 mm thick) exists and most of the upwelled dye returns to the bottom of the trap. At Re = 1,900 the upwelling becomes almost continuous as more of the eddies penetrate deeper into the trap (1–1.25 D). Most of the upwelled dye now escapes from the trap. At Re = 2,900 upwelling is continuous. For A = 1 almost continuous upwelling was observed even at Re = 500. These observations are based on five runs using traps 10 and 11.

For A = 8 upwelling was never observed, even at Re = 20,000 (it was impossible to work at higher Re in the tank available), but there was a progressive thinning of the bottom layer as Re increased. Nine runs using trap 12 were done.

The effect of doubling the wall ratio was examined in five runs with Re between 1,600 and 8,100. Traps 5 and 6 were used. The main result was an increase in the angular velocity of the eddies in the upper zone. This effect was most pronounced at low Re (<4,000) and became less noticeable as Re increased. A possible explanation is that the increased wall thickness allowed a more fully-developed boundary layer to form at low Re but that at higher Re this effect was less pronounced. Thus this is an effect that depends on the wall Reynolds number and not the trap Reynolds number. Since most traps have large wall ratios, this effect is unlikely to be important except for very small traps (such as the ones in laboratory studies, for instance).

Mounting the traps directly on the mooring wire produces effects similar to those caused by increasing the wall thickness. Vortices shed by the wire increased the velocity of water in the trap, especially in the upper zone. Again the effect was most pronounced at lower Re although the Re required for continuous upwelling in traps with A = 3 decreased to 4,000. No similar reduction was observed for traps with A = 5.

Four runs (using trap 7) examined the effect of having a funnel at the bottom of the trap. Re varied between 6,500 and 12,400. The results show that in general the flow was similar to that in flat-bottomed traps, but the Re required for upwelling is slightly lower. At Re = 6,500 eddies penetrate to about two D with circulation induced by the eddies occurring to about 4–4.5 diameters. Upwelling occurs sporadically. At Re = 8,000 the eddies penetrate to 2.5 diameters and the velocity of the induced circulation increases. There is intermittent helical upwelling from various discrete points on the funnel with some, but not all, of the water escaping from the trap. At Re = 10,000 the upwelling is continuous but not vigorous—a good proportion of the upwelled dye still settles to the bottom (the upwelling still does not cover the entire trap bottom)—while at Re = 12,400 all of the dye escapes from the trap even though the activity is still not as vigorous as in the traps with flat bottoms. Thus, although upwelling begins at a lower Re, it is not as vigorous as in the flat-bottomed traps.

TABLE 3. Summary of wave experiments. Trap dimensions are given in Table 1.

Run #	Trap used	Re_H	Re_V
1	8	16,800	11,600
2	8	17,700	12,200
3	8	14,000	9,700
4	5	5,000	17,000
5	1	4,800	18,700
6	3	5,300	14,900
7	6	5,500	17,200
8	9	2,200	1,500
9	2	7,500	13,000
10	4	7,700	5,700

Ten runs examined wave-induced flow; details are given in Table 3. The effects of aspect ratio, wall ratio, and increasing Re were all examined. Wave-induced flow is similar in many respects to that induced by steady flow but because of the vertical motions induced by the wave motions there are some differences and the circulation is somewhat more intense for the same A and Re. The flow is again divided into three regions: an upper zone where the flow is directly coupled to the wave motion, a middle region in which the flow is complex but shows no periodicity, and a bottom zone which may or may not be tranquil, depending on Re. The vertical components of the waves produce some spectacular motion in the upper part of the trap, but their effect in the lower zones is limited, although the depth of eddy penetration is less dependent upon Re and seems to have a slightly greater maximum value (about 3 D). Flow in the

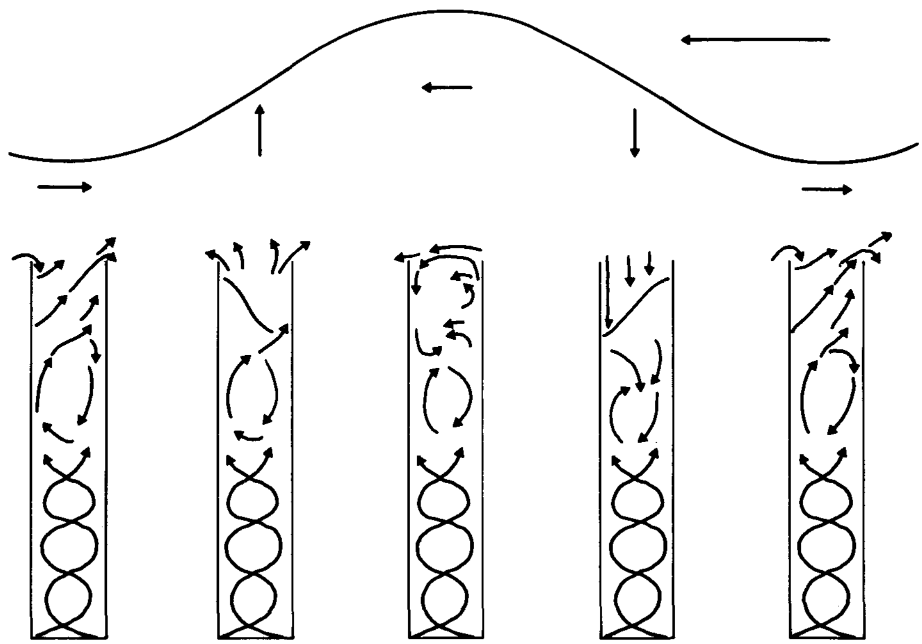

FIG. 3 Trap flow due to wave action. A = 5, Re = 10,000.

trap during the passage of a wave is shown in Fig. 3. As can be seen, eddies form in the upper part of the trap exactly as in steady flow while lower in the trap the circulation is independent of wave phase. The occurrence of upwelling, the activity of the circulation in the middle region, and the thickness of the bottom layer (Table 2) are all better correlated with the horizontal trap Reynolds number, Re_H (where the velocity used is the horizontal component), than with the vertical Reynolds number, Re_V (calculated using the vertical component). There is a tendency for the direction of the upper eddies to reverse as a wave passes, but the vertical motions inhibit complete reversal. The prevailing eddy motion is in the same direction as the wave orbital motion under the wave crest, with only a pause or slight reversal as the wave trough passes. Longer waves might generate true reversals of the eddies.

For A = 5, at Re_H = 2,200, the depth of eddy penetration is 2 D, and the tranquil zone at the bottom is about 2 D thick. At Re_H = 4,800–5,000 the thickness of the tranquil zone decreases to about 1 D and eddies penetrate to 2–2.5 D. At Re_H = 7,700 eddies begin to appear in the middle region and the tranquil region decreases to about 0.5 D, while at Re_H = 12,400 steady helical upwelling occurs in the bottom zone, although at a less vigorous rate than in steady flow at the same Re.

For A = 3, active upwelling, much more vigorous than in the same traps in steady flow, occurs at Re = 5,300–55,000. Again the middle zone is eliminated as the upper eddies penetrate to near the trap bottom. Changing the wall ratio had no visible effect on the flow.

DISCUSSION

The steady flow observations agree quite well with those of Gardner (1980a, 1985), and the observed initiation of upwelling as a function of Re and A is roughly similar to Lau's (1979) observations of resuspension of neutrally buoyant particles. Lau observed resuspension at A = 5 when Re > 5,000, while here the first observed upwelling was at Re = 4,300, at A = 3 upwelling was first observed when Re = 3,500 while an extrapolation of Lau's results gives Re = 4,300, and at A = 8 although Lau observed upwelling at Re = 20,000 none was seen in this study. Since both Lau's and the present results showed considerable variability, more runs might reduce the discrepancies. However at A = 3 it appears that there is a real difference between these results and the extrapolation of Lau's data. The smallest aspect ratio tested by Lau

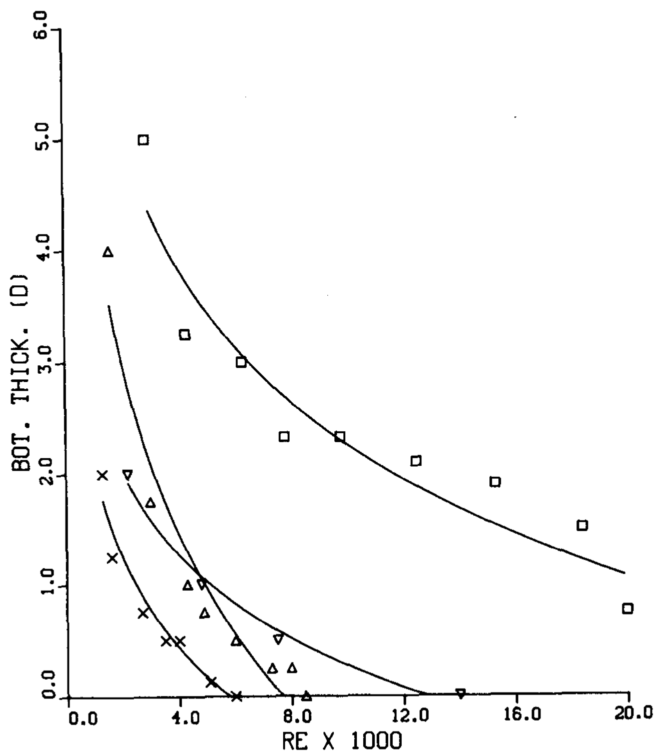

FIG. 4. Bottom layer thickness for the observations in Table 2 and calculated using equations 1-4. Squares are for A = 8, triangles for A = 5, and crosses for A = 3 in steady flow. Wave-induced flow for A = 5 is shown by inverted triangles.

was 4.7, but the new observations show that the eddies generated at the top of the trap penetrated deeper into the trap as Re increased until a limiting value of 2-2.5 D was reached. For traps with aspect ratios of three or less, at large enough Re eddies can induce upwelling directly without having to induce circulation in the middle region of the trap. This could cause resuspension at lower values of Re than Lau's data would indicate.

The observations show that the thickness of the bottom tranquil layer decreases with increasing Re and increasing A (Fig. 4). The data are based on visual observations of the bottom layer thickness, but since no precise measurements were made to determine their variability they are only estimates and should be used with caution. Nevertheless, the trends are clear. The bottom layer is also disrupted by upwelling, which increases in frequency and duration as Re increases. The thinning of the bottom layer can be expressed as a logarthmic function of Re. For A = 8

$$B_T = 18.29 - 1.74*\ln(Re) \qquad r^2 = 0.91 \quad (1)$$

where B_T is measured in trap diameters. Similiar equations can be constructed for A = 5

$$B_T = 20.04 - 2.24*\ln(Re) \qquad r^2 = 0.94 \quad (2)$$

and for A = 3.

$$B_T = 10.22 - 1.18*\ln(Re) \qquad r^2 = 0.94 \quad (3)$$

A similiar equation can be constructed for wave motion with A = 5.

$$B_T = 10.31 - 1.09*\ln(Re) \qquad r_2 = 0.99 \quad (4)$$

These equations are based on the data in Table 2 and are shown in Figure 4. When a range for B_T is given, the midpoint was used. Only the lowest value of Re for $B_T = 0$ was used. Note that neither the intercepts nor the regression coefficients vary monotonically with A. This suggests that if the effect of the aspect ratio is to be included in a formula predicting B_T, the dependence should be at least quadratic. A general equation with a quadratic dependence on A does, in fact, fit the data for steady flow quite well.

$$B_T = 1.11*(19.60-(A-6.23)^2)$$
$$-0.14*\ln(Re)*(16.80-(A-5.90)^2) \qquad r^2 = 0.97 \, (5)$$

Equation 5 was fit using the data in Table 2 for A = 3, 5, and 8. Data for A = 1 and A = 2 were not used since they are not estimates of the minimum Re at which $B_T = 0$. Examination of equation 5 indicates that something occurs when A is about 6, but the actual physical process is not known. Examination of the standardized residuals also shows a distinctive pattern; high values at low Re, a minimum at Re = 2,000-4,000 (depending upon A), and then a steady increase as Re increases. Again, the physical process responsible is unknown. The surface generated by equation 5 is shown in Figure 5. Since the equation predicts nonsensical values for A less than 2 or greater than 0, no data for those values are shown. Note that at A = 10, equation 5 predicts that B_T is independent of Re. This seems physically unlikely and indicates that higher order terms may be needed. Including a quadratic term for ln(Re) improved the fit only slightly however, and given the inexactness of the data it seems pointless to extend the analysis any further. Equation 5 should be taken for what is it, an empirical fit of the data in Table 2; extrapolation of the results to other values of A and Re would be dangerous. Remember also that the val-

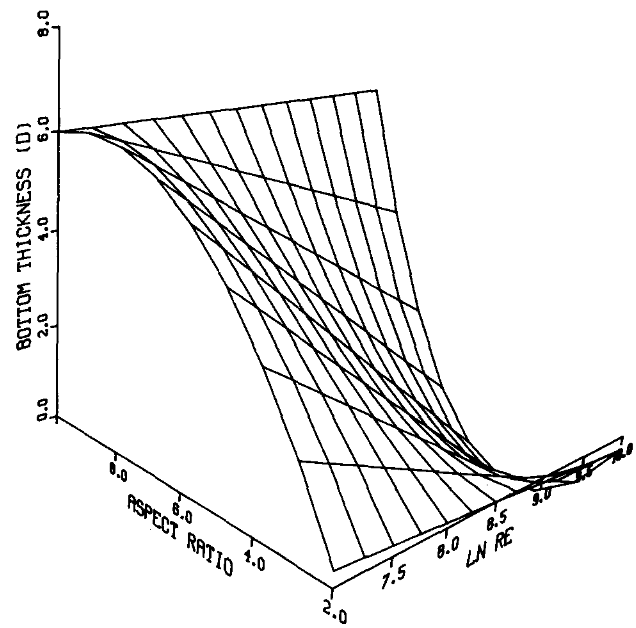

FIG. 5. Bottom layer thickness as a function of A and ln(Re) calculated from equation 5. The contours are at intervals of 0.25 of ln(Re) and at intervals of 1 for A. Note the negative values predicted for small A and large Re.

ues of B_T are higher than those that would exist at equilibrium.

These results agree with Butman's (1986) observation that trap collection efficiency decreased about 50% as Re changed from 2,200 to 4,600 (for A = 3). They show that while at Re = 2,700 eddies only penetrated about 1-1.5 D into the trap and an undisrupted bottom tranquil layer about 1-0.5 D thick existed, at Re = 3,500 upwelling events, which were triggered by eddies penetrating down to or near the bottom, began to occur. Thus the marked decrease in collection efficiency noted by Butman correlates with the initiation of bottom upwelling, lending support to Butman's hypothesis that resuspension was the cause of the large decrease in collection efficiency. It is important to remember that the initiation of upwelling does not preclude deposition. Gardner (1985) has noted that many field experiments have shown that deposition occurs at aspect ratios much less than Lau's data would indicate. Thus although the initiation of upwelling lowers the rate of particle collection it does not stop it. It is also important to keep clear the distinction between upwelling, which is a characteristic of the flow and is what was observed in this study, and resuspension, which is a process that affects the particles. Measurements of trap collection efficiency can be affected by upwelling in two ways; by particle resuspension, and by inhibiting the deposition of particles in the first place. Which of these two mechanisms is more important in Butman's experiments cannot be determined.

Once upwelling begins, further increases in its rate of occurrence seem to have relatively little effect on trap collection efficiency. Butman found almost no difference in collection rates for Re between 4,400 and 19,000. As Butman noted, however, this behavior is difficult to reconcile with her observation that collection efficiency increased by about 40% as A increased from 1 to 2.7 at Re = 10,000. These observations and an extrapolation of Lau's results both indicate that upwelling should have occurred in all of Butman's traps. Apparently in Butman's experiments the degree of upwelling varied enough to affect collection efficiency. One possible explanation is that due to the increased coupling between movement at the bottom of the trap and the eddies at the top the rate of change in the resuspension rate is larger in traps with low aspect ratios (Butman's traps had aspect ratios between 1 and 2.7) than in traps with a higher aspect ratio at the same Re. It may be significant that Butman noted no further increase in collection efficiency for A = 3.6

Upwelling in the traps is a stochastic process probably caused by turbulent fluctations in the flow in the upper part of the trap. If a fluctation is strong enough, it will cause an upwelling event to occur, and the probability of a strong enough fluctation occurring increases with increasing Re. There is probably no critical Re below which upwelling will not occur (unless the flow becomes laminar), but it is less likely to occur at lower Re. For A = 5, I observed no upwelling events at Re = 4,300, but my observations were limited to 10-15 minutes. Given enough time, it is likely that some events would have been observed at lower Re. However, the infrequency of these events at low Re means that except for very slowly settling particles the tranquil layer is permanent. As Re increases, both the frequency and the intensity of the upwelling events increase until there is apparently continuous upwelling over the whole trap bottom. Obviously this is impossible since continuity requires that water come from some place to replace that which is upwelling, but this replacement must occur intermittently at any given location. The increase in frequency and duration of upwelling means that even if a bottom tranquil layer exists, it exists for shorter time periods than at lower Re.

The underlying principle of particle collection in cylindrical traps is that particles are deposited as the result of fluid exchange (Gardner 1980a). Thus, as water is circulated through the upper part of the trap, particles come in contact with the lower tranquil layer, settle through it, and are deposited on the bottom. The presence of the tranquil layer also inhibits resuspension, so the amount of material deposited depends directly on the residence time of fluid in the trap. At low Re this is an accurate description, but at higher Re, as the tranquil layer becomes increasingly disrupted, the theory requires modification. Gardner's (1985) observations of flow at Re = 11,800 (A = 5.2) showed that an intact tranquil layer existed only in the corners of the traps, and presumably deposition occurred there, but I believe that even at Re = 10,000 (for A = 5), the tranquil layer has effectively ceased to exist. Gardner (1985) made an analogy between the tranquil layer and a viscous sublayer, through which particles with large fall velocities settle with only minor changes to their trajectories while slowly falling particles only enter the sublayer as a result of active fluid movement—the turbulent burst and sweep cycles. It seems likely that as Re increases and the tranquil layer is destroyed, the actual viscous sublayer just above the trap bottom must be the layer through which particles settle prior to deposition. Of course, since net deposition does occur, more particles must be deposited than are resuspended. At intermediate Re, where the tranquil layer exists intermittently, particles could still be deposited through the bottom layer as well as through the viscous sublayer during the upwelling events. The exact values of Re for which each of these modes of deposition occurs depends not only on the flow conditions in the trap, but also on the particle settling velocity.

Butman *et al.* (1986) concluded that trap collection efficiency should decrease as the ratio of the fluid velocity (U) to the particle fall velocity (W_P) increases for fixed Re and A. However no experiments were done to test this hypothesis, and their discussion is limited to the effects of eddies on particle transport. The results of this study allow the effects of changing U/W_P on particle deposition through the bottom layer to be at least qualitatively evaluated.

In the absence of resuspension, trap collection efficiency depends on what proportion of particles entering the bottom layer are deposited. This in turn depends on the ratio of the time required for particles to settle to the time between upwelling events. Obviously upwelling may also cause resuspension, thus lowering collection efficiency, but there are no data on particle resuspension in traps so its effects cannot be evaluated. Although no quantitative data are available, the frequency of upwelling events clearly increases with both increases in Re and decreases in A. This means that the frequency of upwelling is a function of trap diameter, trap height, fluid viscosity, and fluid velocity. The time for a particle to settle (P_T) is equal to the thickness of the bottom layer divided by the particle fall velocity. Since B_T is a function of D (note that dimensional units are required, so the values of B_T found from equation 5 must be multiplied by D), Re, and A, P_T is a function of the same parameters as the upwelling frequency, plus W_P. The fact that B_T must be in dimensional units means that particle settling cannot, as flow behavior can, be modeled solely by Re and A, since even for the same Re and A, the thickness of B_T will depend on D. However, since Re is a function of U*D, for Re to remain constant any increase in D will require a corresponding decrease in U, and vice versa. This means that for Re and A to remain fixed with changing D, U/W_P must also change, thus preserving the scaling formulated by Butman *et al.* (1986). This means that U/W_P can be used to predict changes in settling behavior through the bottom layer, as well as changes in particle transport due to eddies. The exact form of this function is not known, even in the absence of resuspension, since the changes in upwelling frequency and duration as a function of Re and A are unknown. Nevertheless, some simple calculations can give a qualitative feel for the biases that might be important in trap collection.

Figure 6 shows the thickness of the bottom layer in mm for various values of D and U for A = 5. Note that the effect of increasing Re on B_T varies depending upon whether U or D is held constant. This is because the values of B_T given by equation 5 are now multiplied by D. At a constant U the value of B_T may not decrease monotonically with increasing D. For instance, for U = 30 mm/s, the value of B_T for a 100-mm trap is greater than for a 50-mm trap. For constant D, however, B_T always diminishes as U increases. If the frequency of upwelling did not also increase with Re (or U for fixed D), particles would be more likely to settle at higher than at lower flow speeds. This is not the case, so as Re increases, upwelling and resus-

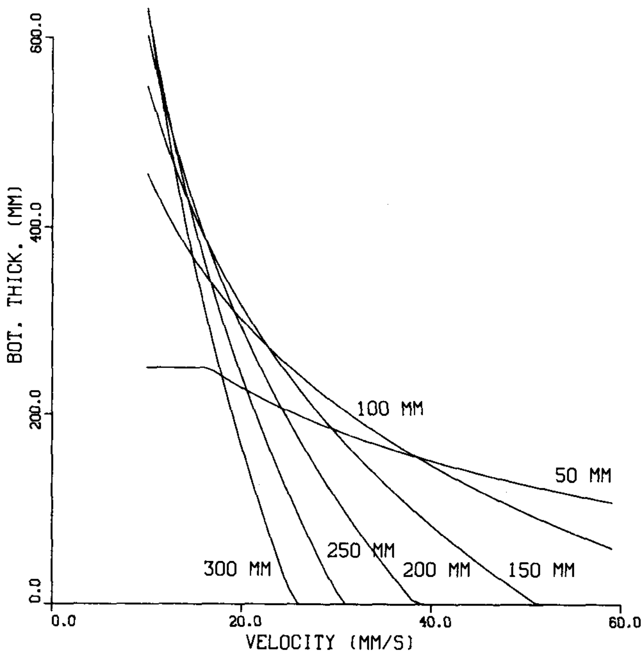

*FIG. 6. **Bottom thickness in mm for various values of velocity and trap diameter for A = 5 calculated using equation 5 multiplied by D. The horizontal segment for the D = 50 mm curve indicates those velocities for which the equation predicts a bottom thickness greater than the trap height.***

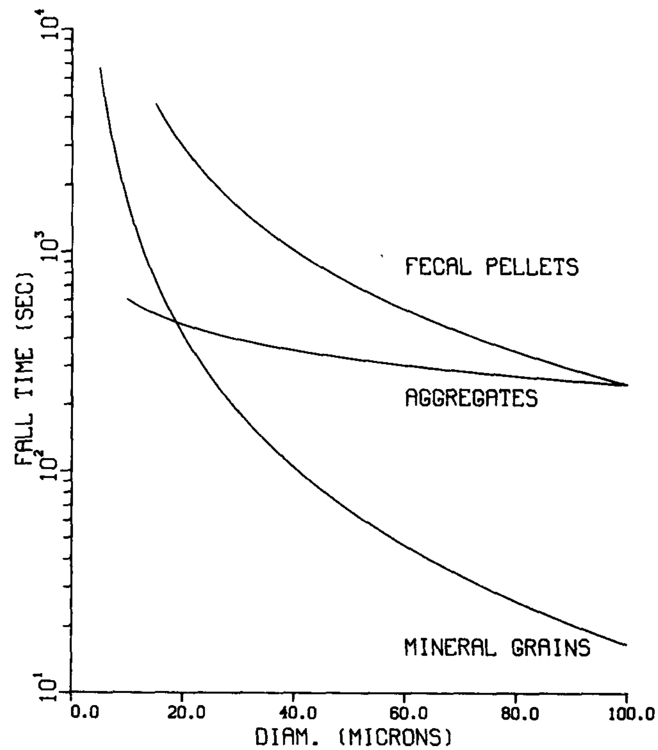

*FIG. 7. **Fall time required for particles to settle through 150 mm. For diameters greater than 100 micrometers, fecal pellets fall more quickly than aggregates.***

pension must increase more rapidly than B_T decreases. Since the tranquil layer can exist continuously only at very low flow velocities even in fairly small traps (for A = 5, upwelling begins at Re = 4,300. This corresponds to U = 86, 43, 29, 22, 17, and 14 mm/s for D = 50, 100, 150, 200, 250, and 300 mm), in many environments U will be large enough, at least part of the time, to destroy the tranquil layer. During these periods deposition is probably mostly through the viscous sublayer, and resuspension of material previously deposited may occur unless the material is removed from the trap, as is the case for the trap in Figure 1. Even without resuspension, it seems likely that, except at very low flow velocities, very slowly settling particles may be deposited only by settling through the viscous sublayer while more rapidly settling particles may be deposited through the tranquil layer as well. This could lead to a bias in favor of collecting more rapidly settling particles if conditions during the deployment vary enough so that there are times when a bottom layer does and does not exist. Figure 7 shows the time required (P_T) for various types of particles to settle 150 mm, the depth of the bottom layer in a trap with D = 100 mm and A = 5 for Re = 4,000. Velocities were calculated using Stokes' Law for the mineral grains, Hawley's (1982) equation 3 for the aggregates, and Small *et al.'s* (1979) equation for the fecal pellets. The diameters given are the equivalent spherical diameters for the fecal pellets. If upwelling does not occur for periods of at least 15 minutes (900 seconds) then aggregates of all sizes could be deposited through the bottom layer but mineral grains less than 14 micrometers and fecal pellets less than 44 micrometers could not, thus biasing the collection against these smaller particles.

If a bottom layer never exists, then all deposition must be through the viscous sublayer. Although processes in the viscous sublayer are not well known, settling behavior should be similar to that in the bottom tranquil layer although the time and length scales are unknown. Since the sublayer is very thin (at most a few mm), the bias in favor of rapidly settling particles may be reduced since the difference in the times required to settle through the layer will be smaller. Although the bias may be small, collection efficiency will also be low due to particle resuspension and the short times available for deposition through the sublayer.

When the tranquil layer is permanent, or persists for time periods much longer than P_T, deposition occurs by particles settling through the tranquil layer. Under these conditions the collection efficiency should be high and little bias in either particle size or particle type should exist in the collected material.

At present there are no data which allow this model to be tested, but it can explain several observations made by other workers. Gardner (1980b) observed an increased percentage of fine material in traps which overcollected material. These traps apparently had turbulence levels lower than those used for his calibration, which could cause an increase in the deposition of fine material as described above. Gardner (1985) also obtained similar results by tilting traps. As the trap was tilted, the depth of eddy penetration decreased, overtrapping increased, and the percentage of fines collected increased. By decreasing the depth of eddy penetration, the frequency of upwelling was diminished, thus allowing more fine material to be deposited.

The presence of a funnel and collection bottle at the bottom of a trap should lead to enhanced collection rates, mainly because deposited material is removed from the pool available for resuspension fairly quickly while the flow behavior is quite similar to that in traps with flat bottoms. In these traps the collection rate will depend almost entirely on the rate at which particles are deposited through either the tranquil layer or the viscous sublayer. Similarly, since wave-induced flow in traps appears to be roughly similar (although somewhat more vigorous) to that generated by steady flow, collection rates may not be appreciably different unless the trap tilts, in which case Gardner's (1985) observations show that collection may be considerably enhanced. Although the fluid motion in traps in oscillatory flow has been described, there are not really enough data to draw any firm conclusions.

CONCLUSIONS

Although the observations are semi-quantitative at best, and the runs were probably too short to reach near-equilibrium conditions, they show that while Gardner's (1980a) theory of particle collection is accurate at low Re, at higher Re it should be modified to include the increasing frequency and intensity of upwelling. As Re increases, the bottom tranquil layer ceases to exist so deposition must occur through the viscous sublayer. At intermediate Re, when upwelling is intermittent, deposition could occur both ways so the collection rate might increase slightly, but there will be an increasing bias in favor of collecting rapidly settling particles. At higher Re both deposition and resuspension are associated with turbulent bursts and sweeps. The balance between the two is a function of the intensity of the turbulence, which causes the net deposition rate to decrease with increasing Re. At the same flow velocities, traps with higher aspect ratios will have less intense circulation at the trap bottom so collection rates will be higher while traps with larger diameters will have lower collection efficiencies than those with smaller diameters. The presence of a funnel and collection bottle at the bottom of a trap only affects the flow slightly, but by removing material from the resuspendable pool, their presence should enhance the collection rate. Wave-induced circulation is similar to that in steady flow, although the decay of B_T with increasing Re is greater, unless the trap is tilted.

Flow behavior in traps can be adequately predicted as a function of A and Re, but particle settling behavior must also be scaled by U/W_P. Although no experimental evidence exists to test this dependence, sample calculations show that for increasing U there may be a substantial bias (favoring rapidly settling particles) in collection efficiency, as long as a tranquil layer exists at least part of the time. If deposition is only through the viscous layer, the bias may be reduced, but collection efficiency will also diminish.

The "best" trap is one that accurately measures both the vertical flux and the distribution of particle types and sizes that contribute to that flux. Given the variations in velocity in many natural settings and the factors affecting trap collection efficiency, it is probably impossible to design a trap which accurately measures both the vertical flux and the distribution of particles comprising that flux under all conditions. If possible, traps should be designed so that the bottom tranquil layer exists for most of the deployment period. This allows a high collection efficiency and minimizes the bias that exists in favor of rapidly settling particles. In most instances this means that several small traps are preferable to a single large trap. If larger traps must be used, they should probably be designed so that upwelling occurs most of the time.

This ensures that all deposition is through the viscous sublayer, and although collection efficiency may be low, the sample should not be too biased in favor of the rapidly settling particles. Compromises in trap design appear to be inevitable, but the trade-offs should be understood before selecting a particular trap.

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